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Safety effects of roundabouts in Flanders: Signal type, speed limits and vulnerable road users

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Abstract

This paper examines the road safety effects of roundabouts built in Flanders between 1994 and 2000. While the overall effect is positive (39% reduction of injury accidents), the results vary considerably with the speed limit on the main and adjacent road (the higher, the more effective) and the pre-roundabout signalization of the intersection (32% reduction with traffic lights versus 44% without).

However, microscopic analysis reveals that roundabouts are not always effective. Serious injury accidents are estimated to increase by 117% on 70 km/h × 50 km/h intersections equipped with signalization before the roundabout. The number of injury accidents involving vulnerable road users is also found to increase (28%) on 50 km/h × 50 km/h junctions that were originally signalized. Moreover, the vulnerable road user is more likely to get fatally or seriously injured. Therefore, it is concluded that traffic lights protect vulnerable road users more effectively than roundabouts, which, in turn, are superior to intersections without signalization.

Keywords: Road safety; Roundabouts; Vulnerable road users

1. Introduction

International studies have unanimously demonstrated that the construction of roundabouts is an effective measure to improve road traffic safety. Robinson et al. (2000) report a reduction in the number of injury accidents between 45 and 87% in Australia, 57 and 78% in France, 25 and 39% in the United Kingdom and 51% in the United States. These positive safety effects are confirmed by Retting et al. (2001) for the United States (76%), Hydén and Várhelyi (2000) for Sweden (46%) and Schoon and van Minnen (1993) for the Netherlands (47%). Recently, the first study for Belgium revealed a 34% reduction in injury accidents with substantial differences related to speed limits (De Brabander et al., 2005). Evidence further shows that the reduction is more outspoken at high speed than at low speed intersections (Ogden, 1996) or at an intersection without traffic lights (Schoon and van Minnen, 1993). In a meta-regression, Elvik (2003) finds slightly smaller safety effects when roundabouts replace previously signalized junctions instead of intersections controlled by yield signs (59% instead of 64% for fatal and 46% instead of 53% for serious injury accidents). In spite of the considerable variation in safety effects, the policy implication seems straightforward: investments in roundabouts are a sure way to reduce the number of accidents and casualties. While this is true on an aggregate level, microscopic analysis reveals a more disturbing truth.

Typically, vulnerable road users[1] are denied access to high-speed roads and thus travel mainly on roads with low speed limits. Roundabouts, on the other hand, are reported to be particularly effective in improving road safety on high-speed roads. Although they are not at all completely ineffective in reducing the overall number of accidents on intersections with low speed regimes, the safety effect on vulnerable road users does seem precarious. The results from international studies seem rather inconclusive. Schoon and van Minnen (1993) report that the reduction in the number of accidents involving cyclists due to roundabouts (30%) is considerably lower than the overall safety improvement (47%). On the other hand, roundabouts reduce the

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[1] Vulnerable road users are defined as pedestrians, cyclists, moped drivers and motorcyclists.

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number of accidents in which at least one pedestrian is involved by 89%. Their analysis does not distinguish between differing speed limits. Hydén and Várhelyi (2000) also found large reductions at roundabouts for bicyclists and pedestrians (60 and 80%, respectively). The expected number of injury accidents for car drivers, however, increased slightly (12%). Their results do not distinguish between pre-roundabout signalization situations, or different speed limits. By contrast, Brüde and Larsson (2000) found a much lower reduction in the number of injury accidents involving bicyclists on single lane roundabouts (21%) and even a substantial increase on multilane roundabouts (112%). Likewise, injury accidents involving pedestrians decreased on single lane roundabouts (79%) and increased on multilane roundabouts (12%). Stone et al. (2002) found that the reduction of pedestrian-vehicle crashes is quite moderate (7%). Their analysis is based on a regression model including only pedestrians.

Improvements or deteriorations in road safety can occur by chance, due to increased exposure or as a result of other policy measures. Using a comparison group of locations with similar characteristics sets off these effects. This allows us to compare the actual accident figures with the number and severity of accidents if the roundabout had not been built. Not doing so is likely to yield an over- or underestimation of the safety effects of roundabouts. The impact on vulnerable road users is also dependent on the pre-roundabout signalization situation (traffic lights or not) for which a clear distinction is made in the analysis. The speed limits on the main and adjacent roads are also a major determinant of the road safety effectiveness of roundabouts. Table 1 shows that this study is the first to take all these effects into account simultaneously.

The article is structured as follows. In the second paragraph, the data set is described. The third paragraph specifies the calculation of the safety effect and checks the reliability of the comparison group. Correcting for trend and regression-to-the-mean effects, the number of accidents is estimated that would have happened without the roundabout. In the fourth paragraph the method to obtain the average safety effects per subgroup is explained. The results are used in the fifth paragraph to calculate the safety effects of roundabouts in terms of the number and injury severity of accidents distinguishing for speed limits and original signalization on the intersection. Specific attention is paid to the impact on vulnerable road users. The final paragraph concludes with some policy implications.

2. Data set

The data set used in this study includes all registered injury accidents that occurred between 1991 and 2001 in Flanders. Table 2 gives an overview of the number of locations and injury accidents. Treated locations were selected from a database made available by the Flemish government. Treatment locations were included in the study only if no adaptations other than the construction of a roundabout were made during the period of analysis. The intersections in the comparison group were selected randomly from a map of Flanders. Next, it was verified that no infrastructural or regulatory changes occurred for the locations of the comparison group as well. The analysis is carried out on 95 roundabouts built between 1994 and 2000 and 230 intersections without roundabouts. This way, calculations can be made at least 3 years before and 1 year after the construction of a roundabout. The intersections are clustered according to the speed limits (50 km/h, 70 km/h, 90 km/h) on the main and adjacent road. A further distinction is made between roundabouts built on signalized and non-signalized intersections. It should be noted that each subgroup has its own comparison group. The data set meets that standard put forward by Hauer (1991), which requires that a comparison group should cover at least 150 accidents in the before period.

3. Effectiveness of one location

The correct calculation of road safety effects requires four steps of data manipulation. The first step in calculating the safety effects of roundabouts is to select a comparison group or groups of intersections that are similar in terms of accidents and hold the same speed and signalization characteristics. To this end, a comparison group of real locations is composed and no safety performance function is estimated since the necessary data are lacking in Flanders.[2] This lack of data stymies the adjustment of safety effects to changes in traffic volume by means of a safety performance function. This may limit the general validity of our results depending on the causes of traffic volume changes:

- First, there is no problem if traffic volume changes are due to purely trend developments since the necessary correction is carried out by traffic volume changes in the comparison group.
- Second, if roundabouts attract new traffic that is *not* moving away from comparison group intersections, then the possible increase in accidents on roundabouts due to higher traffic volumes should be and is correctly assigned to the roundabout.
- Third, however, if traffic volumes (and accidents) shift from locations in the comparison group to the new roundabouts, then the safety effect of the roundabout is underestimated since the number of accidents observed at the intersections in the comparison group is flattered and due to a decrease in traffic volume.
- Finally, if roundabouts are constructed at locations in order to deliberately absorb growing, above-trend traffic volumes (hence, not included in the comparison group locations), then the safety effects are once more underestimated. To avoid this bias, we excluded roundabouts that were constructed simultaneously with new roads connecting to the roundabouts as

[2] The number of intersections (in the comparison groups) for which data on traffic volumes are systematically collected, is relatively small given the total number of intersections in the dense Flemish road network. Moreover, traffic volumes are measured just before the implementation of a roundabout (in order to prepare road diversions). These volumes are available for the years preceding and following construction only if the location is included in the (limited) set of locations for which ADT data are systematically collected. This is, however, rarely the case in Flanders. Finally, data on ADT volumes are even scarcer when intersections in the comparison group or at roundabout locations are located in built-up areas that are maintained by local authorities.

Table 1
Research methodology of main studies

Reference	Country	Effects on vulnerable road users	Distinction speed limit (km/h)	Estimated reduction in the number of injury accidents	Estimated reduction in the number of slight injury accidents	Estimated reduction in the number of serious injury accidents	Estimated reduction in the number of fatal injury accidents	Distinction pre-roundabout signalization	Number of roundabouts	Time period (before and after)	Correction for regression-to-the-mean	Correction for trend
Robinson et al. (2000)	Australia/France/ U.K./U.S.A.	No	No	45–87%/57–78%/ 25–39%/51%	n.a.	n.a.	n.a.	No	n.a.	n.a.	n.a.	n.a.
Retting et al. (2001)	U.S.A.	No	No	76%	n.a.	n.a.	n.a.	Yes	24	n.a.	Yes	Yes
Elvik (2003)	Meta-analysis	No	No	n.a.	45–51%	46–53%	59–64%	Yes	n.a.	n.a.	3 of 28 studies included	
De Brabander et al. (2005)	Flanders (Belgium)	No	50 × 50	39%	37%	28%	n.a.	No	95	1991–2000	Yes	Yes
			70 × 50	15%	14%	36%						
			70 × 70	42%	42%	50%						
			90 × 50	55%	45%	54%						
			90 × 70	59%	40%	72%						
			90 × 90	18%	7%	27%						
Schoon and van Minnen (1993)	Netherlands	Yes	No	47%	65%		76%	Yes	181	1984–1991	No	Yes
Brüde and Larsson (2000)	Sweden	Yes	Yes	n.a.[a]	n.a.	n.a.	n.a.	No	72/182[b]	1994–1997	No	Yes
Hydén and Várhelyi (2000)	Sweden	Yes	No	46%	n.a.	n.a.	n.a.	No	21	1983–1991[c]	No	No
Stone et al. (2002)	U.S.A.	Yes[d]	No	7%	n.a.	n.a.	n.a.	No	1[e]	1993–1999	Yes	Yes
De Brabander and Vereeck	Flanders (Belgium)	Yes	Yes					Yes	95	1991–2001	Yes	Yes

[a] This study examined the level of safety ex post for roundabouts with different speed limits and not the reduction in the number of accidents.
[b] Seventy-two for cyclists and pedestrians/182 for all road users.
[c] Only 6 months after-period.
[d] Only pedestrians.
[e] Simulation based on 23 other intersections.

Table 2
Number of injury accidents at roundabouts with and without signalization before implementation and at intersections with and without signalization (1991–2001)

	Speed limit (km/h): main road × adjacent road					
	50 × 50	70 × 50	70 × 70	90 × 50	90 × 90	Total
Number of roundabouts	45	12	8	11	19	95
Injury accidents at roundabouts	899	298	161	223	544	2125
Number of roundabouts with signalization before	14	5	6	2	6	33
Injury accidents at roundabouts with signalization before	398	212	112	47	265	1034
Number of roundabouts without signalization before	31	7	2	9	13	62
Injury accidents at roundabouts without signalization before	501	86	49	176	279	1091
Number of intersections (comparison group)	59	43	39	40	49	230
Injury accidents at intersections (comparison group)	1589	978	1217	1233	1586	6603
Number of intersections with signalization	27	12	18	19	20	96
Injury accidents at intersections with signalization	873	450	830	751	1120	4024
Injury accidents at intersections with signalization before implementation of roundabout (Hauer-criterion > 150)	245	155	226	226	268	1120
Number of intersections without signalization	32	31	21	21	29	134
Injury accidents at intersections without signalization	716	528	387	482	466	2579
Injury accidents at intersections without signalization before implementation of roundabout (Hauer-criterion > 150)	171	155	176	182	151	835

well as roundabouts where other measures (e.g. signalization, bridges) were taken that could absorb autonomous traffic volume increases.

To determine how well the treated location and its comparison group match, an odds-ratio is computed (Hauer, 1997). This ratio is defined as the ratio of the change in the number of accidents per roundabout before implementation and the change in the number of accidents in its comparison group. A comparison group exists for each subgroup of roundabout locations (clustered by speed limit and signalization type). The odds-ratio can thus be written as

$$\frac{R_{it}/R_{it-1}}{C_{it}/C_{it-1}} \tag{1}$$

with R_{it} is the number of accidents in year t at the roundabout i before construction and C_{it} is the number of accidents in year t at all intersections of the comparison group i.

The average of the odds-ratios over the years before implementation of the roundabout is calculated per roundabout. A comparison group is deemed reliable for a treated location when the average odds-ratio is close to 1 (Hauer, 1997). Fig. 1 shows the average odds-ratio for each individual location (termed as “original odds-ratio”). The original odds-ratios, calculated on the basis of Eq. (1), are acceptable for only 38 locations. This seems to put doubt on the reliability of the comparison groups. However, one important reason for this relatively low number is the underreporting of accidents.[3] Also, the most extreme odds-ratios are observed at locations where the period before the construction of the roundabout is relatively short. Therefore, a lower weight will be given to these places in such a way that they can still be included in the analysis.[4] Since the odds-ratios are more likely to diverge from 1 if few accidents occur,[5] the number of accidents is artificially increased by 1 for those locations where no or one accident happened in a particular year.[6] In Fig. 1,

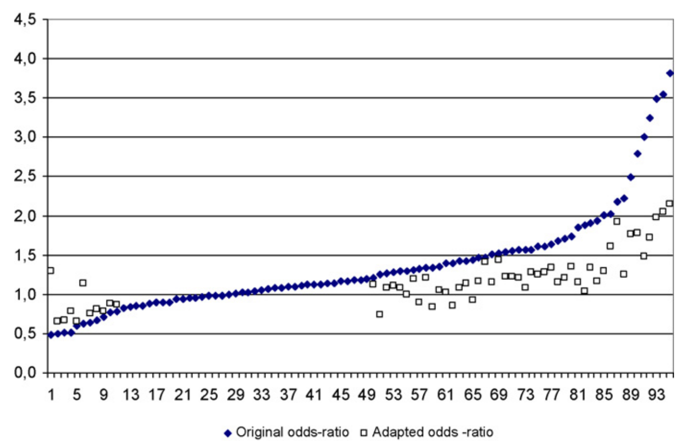

Fig. 1. Original and adapted odds-ratios of roundabout comparison groups (Flanders, 1991–2002).

[3] For example, a comparison of the official accident numbers with data from the Antwerp police reveals an underreporting of injury accidents of 66% in 2000 (Antwerp Police, 2002, p. 3).

[4] See Section 4 where the results of each individual location are combined per subgroup.

[5] In that case, the odds-ratio is more likely to diverge from 1 since a single accident in the following year has a stronger impact on the odds-ratio.

[6] There is only 1 accident added during *all* years of the analysis. Obviously, this artificial accident is excluded in the further calculations of the effectiveness. It is used here to demonstrate the impact of one additional accident on the odds-

the odds-ratios, including these additional artificial accidents, are termed "adapted odds-ratio". This adjustment increases the number of locations with reasonable adapted odds-ratios to 64 or two-thirds of all cases and leads to a higher reliability of our comparison groups. Obviously, the other locations could be excluded. However, this would lead to a bias in the safety effect since information would be unduly neglected. Moreover, as mentioned, the few-accident locations will be given a lower weight in the meta-analysis.

The second step is to produce data on the number of injury accidents that would have occurred if the roundabout had not been built. Obviously, trend and regression-to-the-mean effects affect the outcomes. The latter is likely to occur since most roundabouts are suggested to be built at black spots where the level of accidents is above average (Geurts et al., 2005). The reduction of injury accidents can then not be entirely attributed to the roundabout because this would lead to an efficacy bias (Hauer, 1997). Therefore, following Hauer et al. (2002),[7] the expected number of accidents (as if the roundabout had not been built and correcting for regression-to-the-mean) is computed as

$$\rho_{i\text{b}} = w(\mu_{R_i+C}T) + (1-w)\left(\sum_{t=1}^{T} R_{it}\right) \tag{2}$$

with $\rho_{i\text{b}}$ is the expected number of accidents at the roundabout after correction for regression to the mean, μ_{R_i+C} the average number of accidents per year for the comparison group (C) including the accidents at the roundabout (R_i), T the number of years considered, R_{it} the number of accidents in year t at the roundabout i, $(1-w)$ the weight assigned to the number of accidents at the roundabout, w the weight assigned to the mean number of accidents in the comparison group, which equals $(1 + k_i\mu_{R_{ii}+c}T)^{-1}$

If $w = 0$, then the expected number of accidents equals the observed number of accidents at the roundabout. Hence, there is no correction. If $0 < w < 1$, then the expected number of accidents lies between the observed number and the mean number expected. The overdispersion parameter, k_i, is computed as

$$k_i = \frac{\sigma^2 - \mu_{(R_i+C)}}{\mu^2}. \tag{3}$$

Overdispersion relaxes the assumption of a Poisson distribution of accidents. If the overdispersion parameter is negative,[8] Eq. (2) does not result into a regression to the mean, but into a correction away from the mean. In one subgroup of roundabouts (50 km/h × 50 km/h on intersections without traffic lights), a negative value for k was observed for the accidents with at least one fatal or seriously injured casualty. Therefore, a simulation was made for each individual location using different values of k_i (0.2, 0.5 and 0.9). The results of the meta-analyses for different values of k showed an extremely narrow range of effectiveness and confidence interval. In other words, the effect of a difference in weights (w in Eq. (2)) on effectiveness is negligible. Therefore, the effectiveness for this type of location remains included in Table 3.

The third step is to adjust the number of accidents for the trend. Since other traffic policy measures also affect road safety, the total reduction of accidents observed cannot be attributed entirely to the roundabouts. However, the trend can be derived from the evolution in accidents at similar places, i.e. the comparison group. Therefore, the next step is to calculate the effectiveness ratio (φ). The numerator in Eq. (4) corrects for the regression-to-the-mean while the denominator takes the trend into account:

$$\varphi = \frac{R_{i\text{a}}/\rho_{i\text{b}}}{C_{i\text{a}}/C_{i\text{b}}} \tag{4}$$

with $R_{i\text{a}}$ is the number of accidents at roundabout i after implementation, $\rho_{i\text{b}}$ the number of accidents at roundabout i before implementation and after correction for regression-to-the-mean, $C_{i\text{a}}$ the number of accidents in the comparison group after the roundabout was built and $C_{i\text{b}}$ is the number of accidents in the comparison group before the roundabout was built.

The 0.95 confidence interval for φ is calculated as $\exp[\ln((R_{i\text{a}}/\rho_{i\text{b}})/(C_{i\text{a}}/C_{i\text{b}})) \pm 1.96s]$. Fleiss (1981) and Elvik (1995) have shown that the effectiveness ratio follows a lognormal distribution, hence $s^2 = (1/R_{i\text{a}}) + (1/\rho_{i\text{b}}) + (1/C_{i\text{a}}) + (1/C_{i\text{b}})$.

Eq. (4) is not only instrumental in determining the effectiveness of roundabouts with respect to the number of accidents. The calculations can also be reiterated for each type of location (speed limits, with or without signalization before implementation), injury severity (light, serious and fatal) or road user type.

4. Meta analysis per subgroup of locations

The final step is to calculate the overall effectiveness ratio by aggregating ratios of individual roundabouts. Aggregation should be applied carefully since valuable information is likely to get lost. Indeed, microscopic analysis is about to falsify the general claim of the effectiveness of roundabouts. Therefore, ratios are calculated for each subgroup. Such an approach reveals, for example, that the effectiveness is largely dependent on the starting situation (intersection with or without signalization) or that the construction of a roundabout may sometimes actually increase the number of road accidents.

The effectiveness per subgroup is the weighted average of the results over the different years. The weight w_i assigned to the group of roundabouts is the inverted value of the variance s_i^2. Locations where many accidents happen are thus given a greater weight. For n locations, the overall number of accidents that remain (η) after the implementation of roundabouts is calculated as follows (Fleiss, 1981 and Elvik, 1995):

$$\eta = \exp\left[\frac{\sum_{i=1}^{n} w_i \ln((R_{i\text{a}}/\rho_{i\text{b}})/(C_{i\text{a}}/C_{i\text{b}}))}{\sum_{i=1}^{n} w_i}\right] \tag{5}$$

ratio, given the underreporting of the number of accidents (see Footnote 3). The underreporting of accidents has less impact for the locations in the comparison group because of its size.

[7] The computation here is comparable since we do not use a safety performance function but a real comparison group.

[8] A negative overdispersion is impossible from a theoretical point of view. However, since real locations are used in the comparison group – contrary to using a safety performance function – this may occur in reality.

Table 3
Reduction of injury accidents (confidence interval = 0.95)

	Speed limit (km/h): main × adjacent road					
	50 × 50	70 × 50	70 × 70	90 × 50	90 × 90	Total
Injury accidents at roundabouts	43 (32, 52)**	4 (−24, 25)	55 (25, 72)**	62 (47, 73)**	49 (35, 59)**	39 (31, 45)**
With signalization before	36 (11, 54)**	−4 (−40, 23)	86 (70, 96)**	43 (−6, 70)	40 (17, 57)**	32 (19, 43)**
Without signalization before	45 (33, 56)**	21 (−26, 50)	−2 (−95, 46)	69 (53, 79)**	56 (39, 68)**	44 (34, 52)**
Serious injury accidents at roundabouts	3 (−43, 35)	−38 (−161, 27)	65 (9, 87)*	34 (−28, 64)	30 (−12, 54)	17 (−6, 35)
With signalization before	26 (−162, 39)	−117 (−407, 7)	66 (−6, 89)	75 (−21, 95)	37 (−21, 67)	13 (−28, 41)
Without signalization before	14 (−40, 47)	23 (−102, 81)	61 (−124, 93)	34 (−28, 66)	30 (−12, 56)	20 (−10, 43)
Light injury accidents at roundabouts	44 (33, 54)**	6 (−24, 29)	47 (10, 69)*	50 (25, 67)**	40 (23, 54)**	38 (30, 45)**
With signalization before	37 (12, 56)**	−1 (−37, 29)	83 (62, 92)**	30 (−51, 67)	20 (−12, 43)	31 (15, 44)**
Without signalization before	47 (34, 58)**	18 (−40, 52)	−25 (−154, 38)	56 (29, 73)**	60 (41, 72)**	46 (36, 55)**

* Statistically significant at 0.05.
** Statistically significant at 0.01.

5. Results

5.1. Effectiveness of roundabouts

Table 3 presents the average reduction in injury accidents due to roundabouts. Two major groups of locations are distinguished according to the original signalization situation. Further distinctions are made in accordance with the speed limits on the main and adjacent road.

Table 3 leads to the following conclusions:

- In general, roundabouts reduce the number of injury accidents by 39% in Flanders. This result differs slightly, but positively from a previous study (De Brabander et al., 2005) because recent accident data were added and some locations were removed (in particular when the pre-roundabout signalization situation on the intersection is unknown). While roundabouts lead to a statistically significant ($p < 0.01$) decrease in accidents at every type of junction, the safety effects differ significantly depending on the speed limit regime. The strongest reduction in road accidents can be observed at intersections with high speed limits (90 km/h × 50 km/h, 90 km/h × 90 km/h, and 70 km/h × 70 km/h).
- However, the safety effect is largely dependent on the original signalization situation. Roundabouts built at intersections without traffic lights reduce the number of injury accidents by 44% compared to 32% with signalization. Once again, the largest improvements are observed on high-speed roads without signalization on the original intersection (90 km/h × 50 km/h and 90 km/h × 90 km/h).
- The improvements in traffic safety due to roundabouts can and should also be judged in terms of injury severity. To avoid interference of the number of casualties involved in one accident with the effectiveness ratio, the accidents were labelled in accordance with the most serious injury. The outcomes for serious injury accidents are mixed. Due to the relatively low number of accidents, none of the reduction percentages is statistically significant at 0.05, but the best estimates indicate that roundabouts are ineffective in reducing severe injury accidents at 70 km/h × 50 km/h intersections previously signalized. Actually, the model predicts an estimated increase of severe injuries by 117% (reduction: −407, 7%). At the very least, it is reasonable to conclude that the replacement of traffic lights by roundabouts on 70 km/h × 50 km/h intersection is a measure with uncertain effects. In general, however, the number of serious injury accidents is reduced by 17%. The only statistically significant reduction is found on 70 km/h × 70 km/h intersections.
- The number of light injury accidents, on the other hand, is significantly reduced in general by 38% ($p < 0.01$). Results are positive and significant for the subgroups as well. Overall, roundabouts reduce the number of light injury accidents by 31% when they replace traffic lights up to 46% on intersections without signalization. The largest effect (60%) is again observed on 90 km/h × 90 km/h intersections without traffic lights.

Finally, the confidence intervals of the estimated reduction in the number of accidents need some further careful analysis. The main policy goal of this study is to identify those locations where roundabouts lead to a significant improvement in road safety. Obviously, it would be unwise to invest resources in the construction of roundabouts at locations with reported negative or low safety effects (e.g. locations of 70 km/h × 50 km/h). Efficient use of public resources does not necessarily lead to investments in location types with the highest point estimate since confidence intervals may be overlapping. For example, consider the reduction of injury accidents on intersections with no signalization prior to the roundabout in the 50 km/h × 50 km/h and 90 km/h × 90 km/h subgroups. The point estimates indicate that the reduction for the 90 km/h × 90 km/h subgroup is higher than for the 50 × 50 (56 and 45%). However, the confidence intervals show that the lowest expected reduction in the 90 km/h × 90 km/h subgroup is 39%, while the highest in the 50 km/h × 50 km/h subgroup is 56%. In practice, this implies that there is a chance, which policy makers should consider, that roundabouts at 50 km/h × 50 km/h intersections are safer. Furthermore, in a full cost-benefit analysis, other elements should be accounted for. Examples are the absolute number of injury accidents, the number of injured casualties per accident or the age of road victims which could differ significantly between subgroups of locations. It follows that the effectiveness' calculations are a necessary but only first step in the policy decision-making process.

5.2. Accident analysis of vulnerable road users

A second purpose of this article is to measure the effect of roundabouts on vulnerable road users. For obvious reasons, they travel mostly on low speed roads and are often denied access to high-speed roads. Therefore, the analysis focuses on injury accidents at 50 km/h × 50 km/h intersections. The results in Table 4 show that the overall safety effect of roundabouts is positive. The left column reiterates the results from Table 3. The right column shows that the reduction of accidents involving vulnerable road users is estimated at 14%. However, detailed analysis reveals that this reduction is largely due to the construction of roundabouts on intersections that were not equipped with traffic lights before. By contrast, the traffic safety situation of vulnerable road users has worsened by replacing traffic lights with roundabouts. An increase of 28% in injury accidents is the best estimate for these intersections. Moreover, the largest part of the confidence interval indicates an increase in the number of accidents. Therefore, it is concluded that roundabouts are less effective than traffic lights in protecting vulnerable road users who typically travel on low speed roads and intersections.

Table 4
Reduction of injury accidents with vulnerable road users at 50 km/h × 50 km/h intersections (confidence interval = 0.95)

	Speed limit: 50 km/h × 50 km/h	
	Total	With vulnerable road users
Injury accidents at roundabouts	43 (32, 52)*	14 (−8, 32)
With signalization before	36 (11, 54)*	−28 (−100, 18)
Without signalization before	45 (33, 56)*	27 (3, 44)*

* Statistically significant at 0.01.

Even if the number of injury accidents is reduced (which as just demonstrated is not always the case), the consequences per accident seem direr. Table 5 shows the number of casualties per injury accident before and after construction of a roundabout corrected for the trend and regression to the mean effects. A distinction is made between accidents with and without vulnerable road users. While the implementation of roundabouts at 50 km/h × 50 km/h intersections reduces the risk of getting fatally or seriously injured when involved in a serious accident without vulnerable road users, it is increasing the risk of light injuries regardless of the signalization situation beforehand. So, roundabouts shift the risk from serious to light injuries in accidents involving at least one serious or fatal casualty. Fur-

Table 5
Casualties per injury accident at 50 km/h × 50 km/h intersections before and after the construction of roundabouts

Accidents	Without vulnerable road users		With vulnerable road users	
	Before	After	Before	After
With signalization				
With fatal and serious injuries				
Fatal	0.10	0.00	0.03	0.17
Serious	1.10	1.00	0.97	1.00
Light	0.86	1.00	0.16	0.33
With only light injuries				
Light	1.63	1.73	1.03	1.08
Without signalization before				
With fatal and serious injuries				
Fatal	0.11	0.00	0.12	0.19
Serious	1.39	1.22	0.97	0.81
Light	0.39	1.00	0.06	0.06
With only light injuries				
Light	1.51	1.33	1.09	1.02

thermore, while the chance of light injuries in a light injury accident is reduced at intersections without previous signalization, it has increased at non-signalized junctions.

Unfortunately, these positive safety effects do not apply to vulnerable road users. They are more likely to die when involved in a serious accident. After the construction of a roundabout, the number of fatal casualties per serious injury accident quintuples from 0.03 to 0.17 on intersections with previous signalization and increases by more than half from 0.12 to 0.19 on intersections without.

These different safety effects, depending on the type of road user, are important since many efforts in road safety are targeted at specific groups. Such policy approach seems rational since the probability of a fatal accident suffered by vulnerable road users is between 3 and 30 times higher than average.[9] If the government wants to pursue a policy protecting vulnerable road users,[10] then it may wish to take these results into account. Not only give roundabouts rise to more accidents with vulnerable road users on certain types of intersection, the injury severity per accident may increase as well. Since the subgroup of low speed intersections contains most data, i.e. roundabouts and accidents, the findings of this study will have a huge impact on the social efficiency of roundabouts.

6. Discussion

This paper examines the road safety effects of roundabouts built in Flanders between 1994 and 2000. To that end, the reductions in the number of accidents were calculated distinguishing for injury severity, speed limit regime on main and adjacent road, pre-roundabout signalization situation on the intersection and road user type. In accordance with the state-of-the-art, trend and regression-to-the-mean effects were eliminated before presenting the safety effects. Our estimation method does not explicitly account for traffic volume changes (due to lack of data). This may lead to an underestimation of safety effects if traffic (and accidents) shifts from comparison group locations to roundabouts or if roundabouts are constructed deliberately to absorb growing traffic volumes (not captured by the trend). If so, some accidents are incorrectly assigned to the roundabout. On the other hand, growing traffic on roundabouts due to trend or autonomous developments is correctly captured. Furthermore, roundabouts constructed to deliberately absorb growing traffic were excluded from the study. Admittedly, our results would be more generally valid if traffic volume changes could and would have been taken into account.

In general, roundabouts are found to reduce the number of injury accidents by 39%, severe injury accidents by 17% and light injury accidents by 38%. But the safety impact differs significantly depending on the speed limit regime and the pre-roundabout signalization situation as well as the road user type. Roundabouts are most effective at intersections with high speed limits on the main and adjacent road. The most substantial reductions in the number of injury accidents are found at 90 km/h × 50 km/h (62%) and 70 km/h × 70 km/h (55%) intersections. Smaller roads (50 km/h × 50 km/h or 70 km/h × 50 km/h) enjoy an effectiveness of 43 and 4%, respectively. The impact is also dependent on the situation before the roundabout with better results if the intersection was not signalized (44% versus 32%).

Similar results are found for serious and light injury accidents. The overall reduction of light injury accidents by 38% comprises a reduction by 31% on previously signalized intersections compared to 46% on junctions without traffic lights. But there are exceptions. The largest reduction in light injury accidents (86%) is observed on 70 km/h × 70 km/h intersections previously signalized. By contrast, roundabouts built on 70 km/h × 50 km/h intersections reduce the number of serious injury accidents by 23% if no signalization was in place, but give rise to a 117% increase when they replace an intersection with traffic lights.

Vulnerable road users, who typically travel on smaller roads with lower speed limits, are in some cases more likely to become victims of a road accident after the construction of a roundabout. For example, the number of accidents involving vulnerable road users is up by 28% on 50 km/h × 50 km/h intersections (the largest subgroup) when there used to be traffic lights. Although the total number is down by 14%, the risk of getting more seriously injured when involved in an accident has also increased from 3 to 17 fatalities per 100 injury accidents on previously signalized junctions and 12 to 19 on intersections without traffic lights before.

From a policy perspective, it is relevant to learn that roundabouts are effective in most cases and ineffective in some. Roundabouts may increase the number of severe injury accidents depending on the existing speed limits and signalization on the intersection. Furthermore, they give rise to an increase of injury accidents involving vulnerable road users when they replace traffic lights. For example, since the medical costs of vulnerable road users are above median,[11] policy-makers may rationally decide to invest more in traffic safety of vulnerable road users. In other words, vulnerable road users may be given greater weight in traffic safety design. Since roundabouts give rise to more accidents with vulnerable road users on 50 km/h × 50 km/h intersections as well as more serious injuries, the balance of costs and benefits may just tip over to traffic lights instead of roundabouts.

[9] A common measure is the fatality rate, i.e. the number of road fatalities per billion passenger kilometres. In Flanders, the average fatality rate is 11, for pedestrians 85, for cyclists 32, for moped drivers 126 and for motorcyclists 344. The serious injury rates for the vulnerable road users are even higher. So, compared to other European countries, traffic risks are considerably higher (Ministerie van de Vlaamse Gemeenschap, 2001, p. 159).

[10] The introduction of strict liability in Belgian traffic legislation in 2001, while unmistakably inducing pedestrians to adopt suboptimal ex ante levels of care, is a prime example of a government policy favouring vulnerable road users ex post (Van Dam, 2001).

[11] In Flanders, the median medical cost of a road accident victim suffering serious injuries is 8.970 euro. For vulnerable road users, the median cost amounts to 11.391 euro. Vulnerable road users spend comparatively 2 more days in hospital. Source: based on CM-database (2002).

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